Unit 9
Animal Form and Function

Chapter 37: Neurons, Synapses, and Signaling

Overview: Lines of Communication

- **Neurons** are nerve cells that transfer information within the body
- Neurons use two types of signals to communicate:
  - Electrical signals (long distance)
  - Chemical signals (short distance)
- Interpreting signals in the nervous system involves sorting a complex set of paths and connections
- Processing of information takes place in simple clusters of neurons called **ganglia** or a more complex organization of neurons called a **brain**

Concept 37.1: Neuron structure and organization reflect function in information transfer

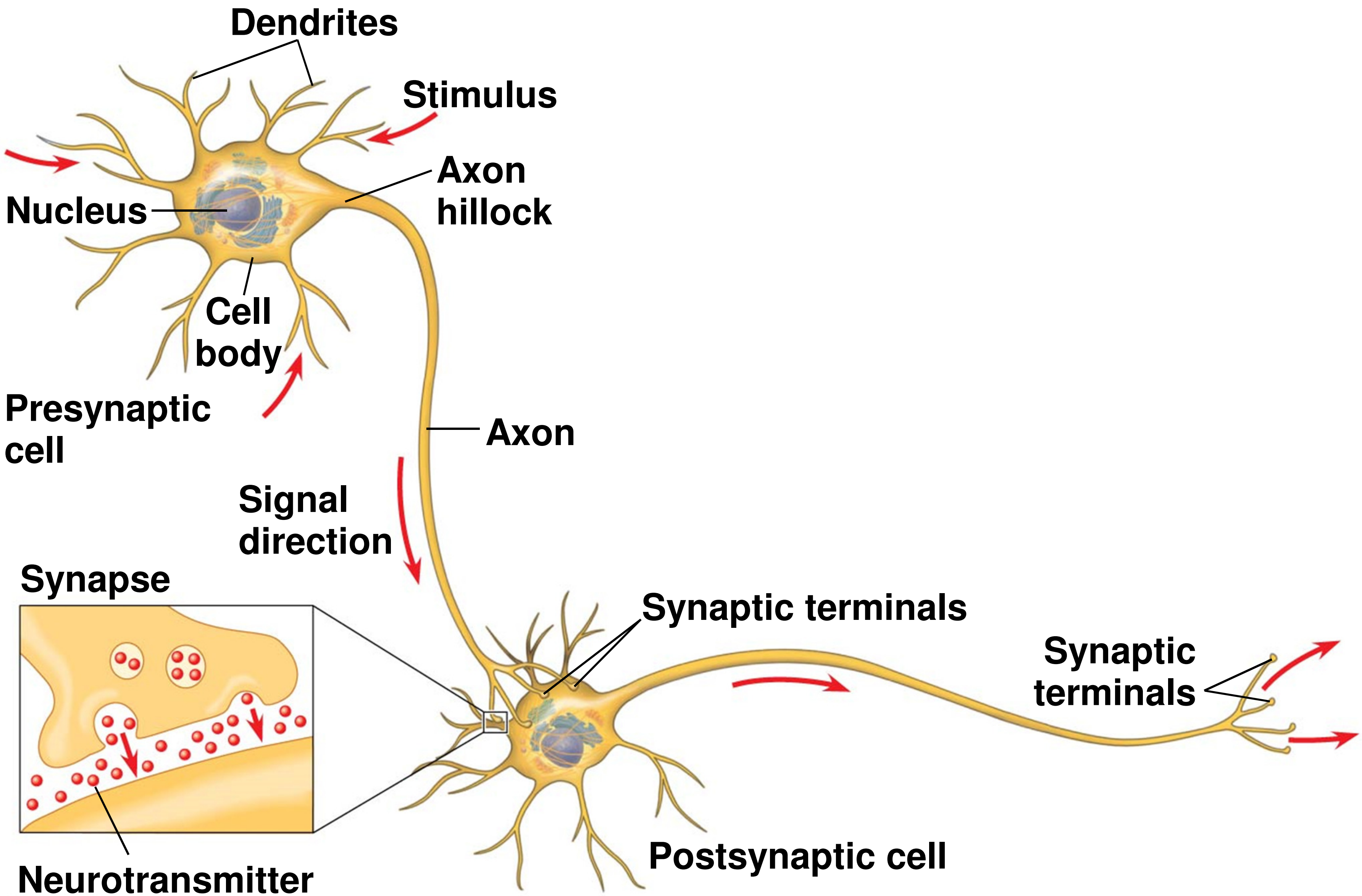
- The neuron is a cell type that exemplifies the close fit of form and function that often arises over the course of evolution

Neuron Structure and Function

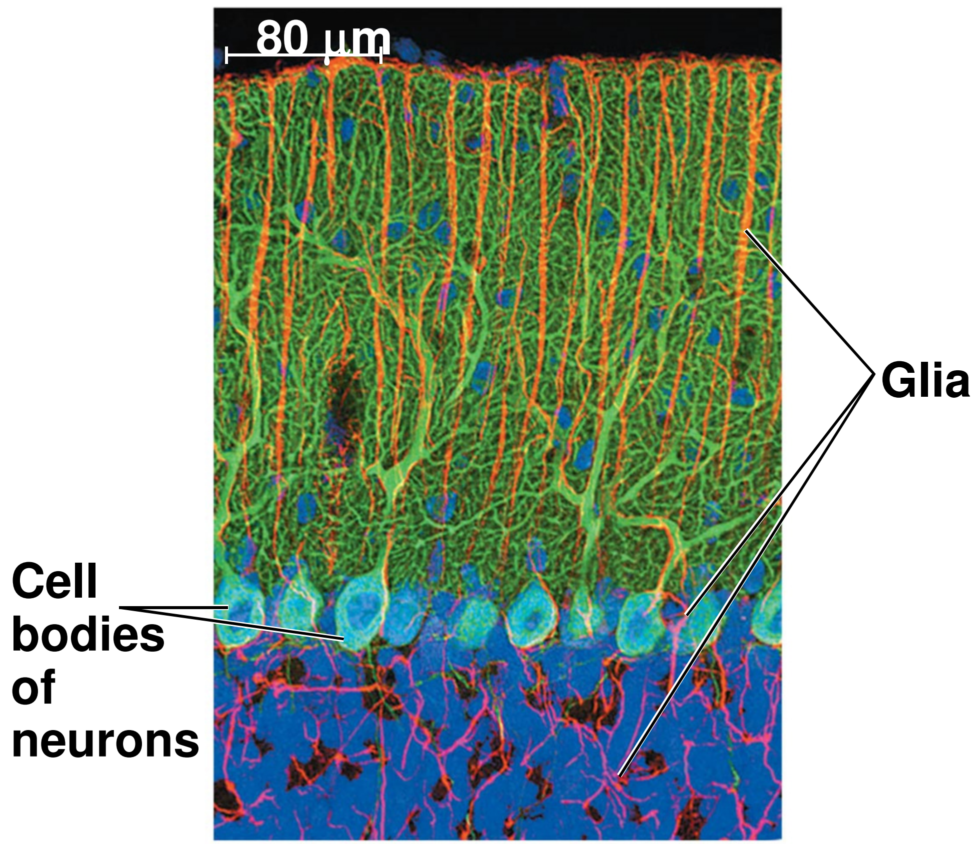
- Most of a neuron's organelles are in the **cell body**
- Most neurons have highly branched extensions called **dendrites**
  - <u>Receive</u> signals from other neurons
- The neuron also has a single **axon,** a much longer extension
  - <u>Transmits</u> signals to other cells
- The cone-shaped base of an axon, where signals are generated, is called the axon hillock

- The branched ends of axons transmit signals to other cells at a junction called the **synapse**
  - The part of each axon branch that forms this junction is a *synaptic terminal*
- At most synapses, chemical messengers called **neurotransmitters** pass information from the transmitting neuron to the receiving cell
  - Transmitting neuron = *presynaptic cell*
  - Neuron, muscle, or gland cell that receives signal = *postsynaptic cell*

Figure 37.2

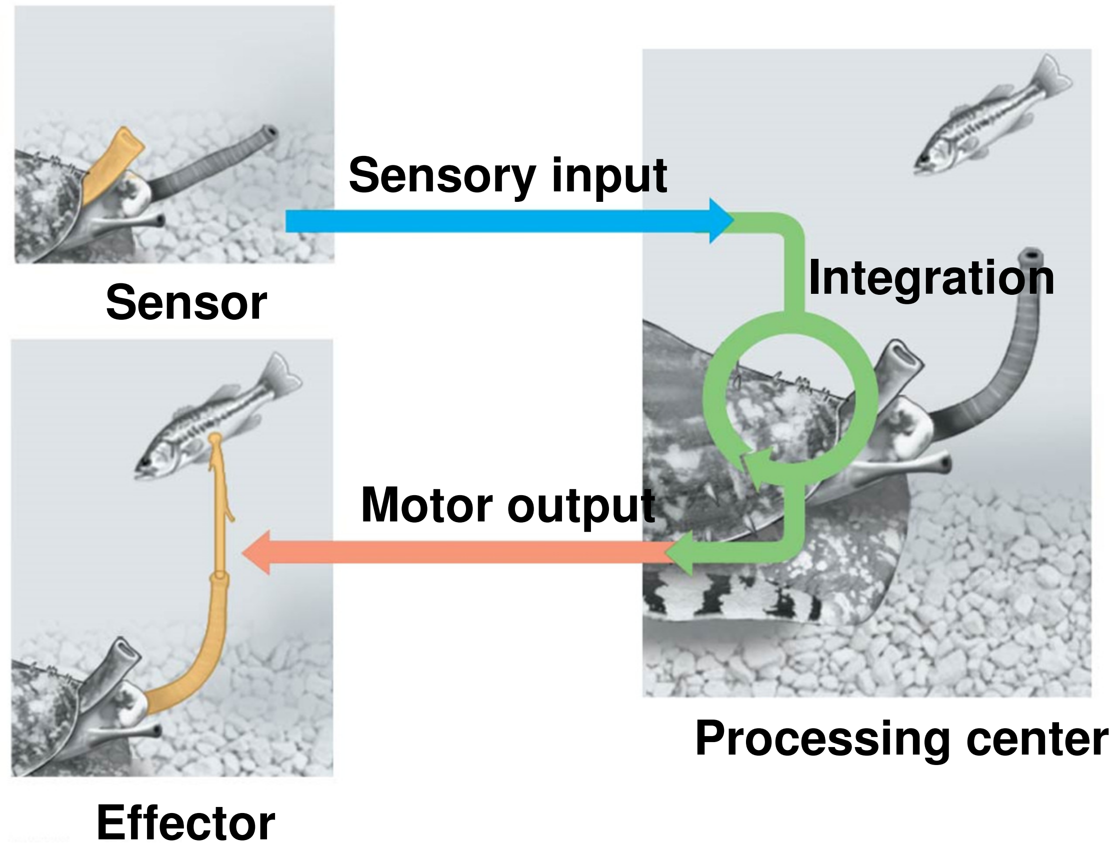

Dendrites
Stimulus
Axon hillock
Nucleus
Cell body
Presynaptic cell
Axon
Signal direction
Synapse
Synaptic terminals
Synaptic terminals
Neurotransmitter
Postsynaptic cell

- Neurons of vertebrates and most invertebrates require supporting cells called **glial cells**
  - Nourish neurons
  - Insulate axons
  - Regulate extracellular



Introduction to Information Processing

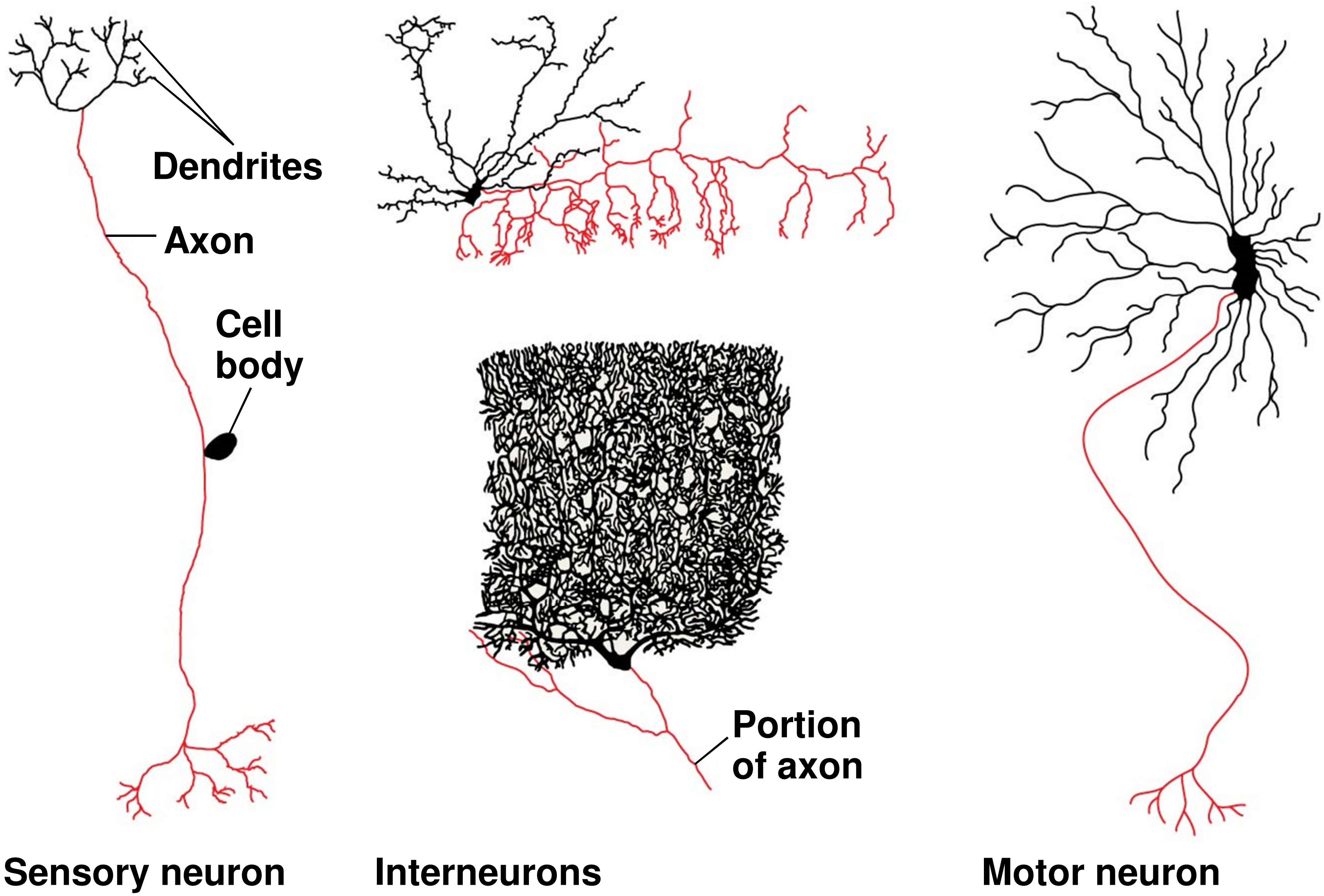
- Nervous systems process information in three stages
  1. Sensory input
  2. Integration
  3. Motor output



- **Sensory neurons** transmit information from eyes and other sensors that detect external stimuli or internal conditions
  - Stimuli include light, sound, touch, smell, blood pressure, muscle tension
- This information is sent to the brain or ganglia, where **interneurons** integrate the information
  - Analyze and interpret
- Neurons that extend out of the processing centers trigger muscle or gland activity
  - For example, **motor neurons** transmit signals to muscle cells, causing them to contract

- In many animals, neurons that carry out integration are organized in a **central nervous system (CNS)**
  - Brain and a longitudinal nerve cord
- The neurons that carry information into and out of the CNS form the **peripheral nervous system** (**PNS**)
  - PNS neurons, bundled together, form **nerves**

Figure 37.5



Dendrites
Axon
Cell body
Portion of axon
Sensory neuron
Interneurons
Motor neuron

Concept 37.2: Ion pumps and ion channels establish the resting potential of a neuron

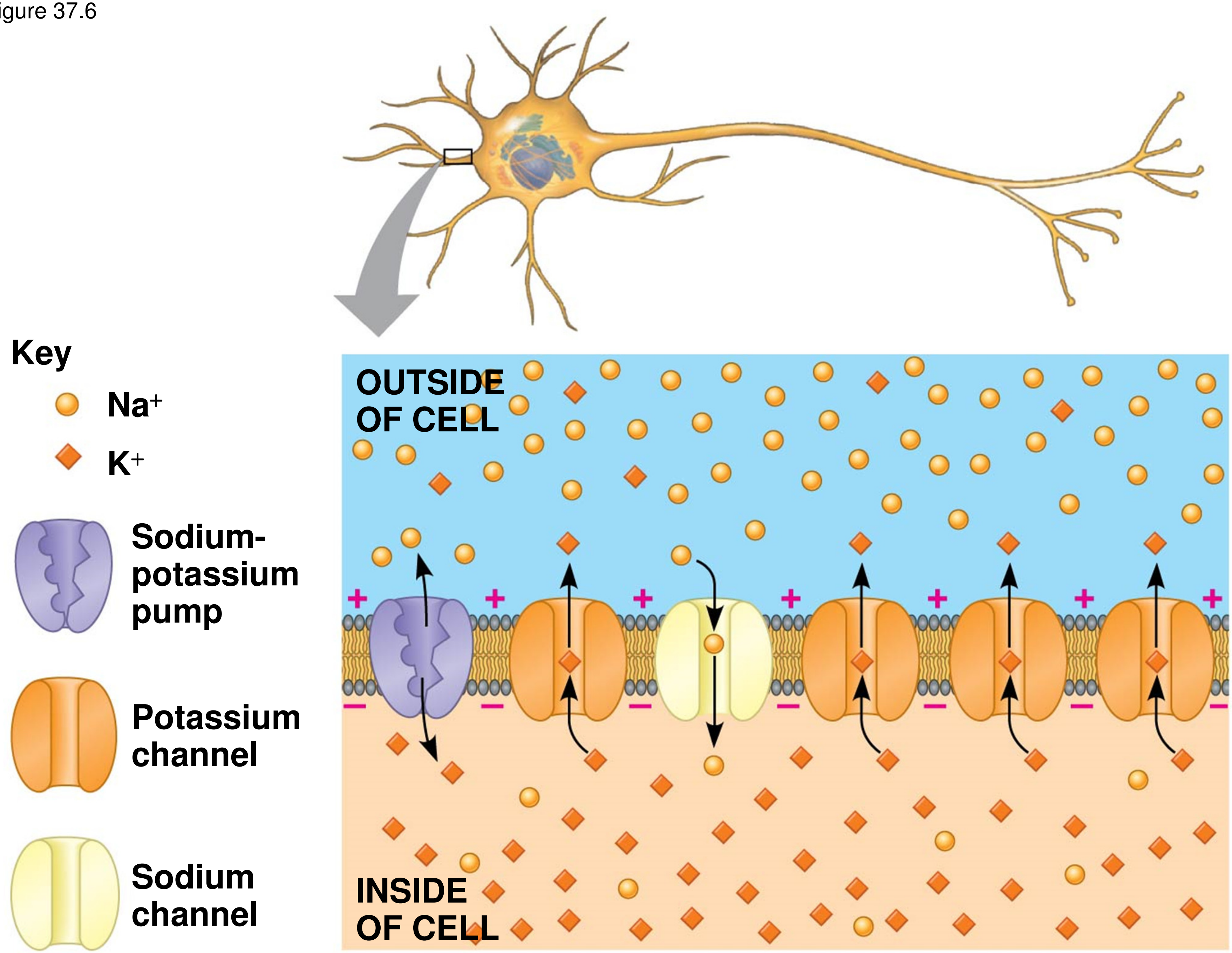
- The inside of a cell is <u>negatively</u> charged relative to the outside
- This difference is a source of potential energy, termed **membrane potential**
- The **resting potential** is the membrane potential of a neuron not sending signals
- Changes in membrane potential act as signals, transmitting and processing information

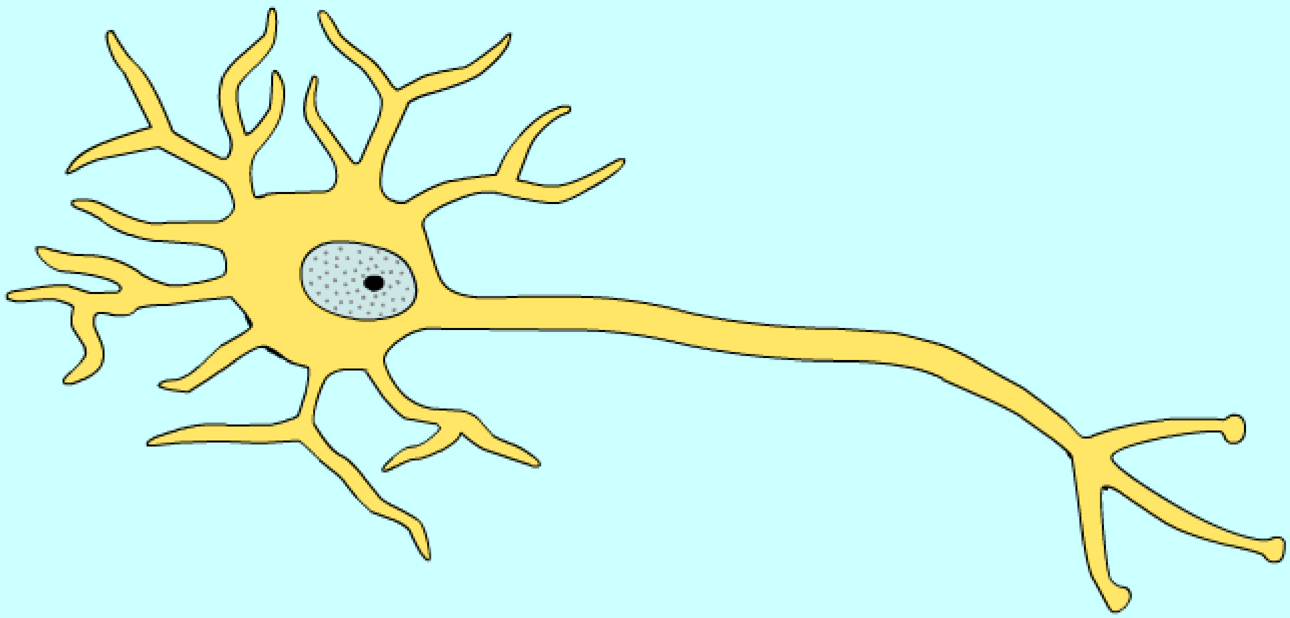
Formation of the Resting Potential

- K^+ and Na^+ play an essential role in forming the resting potential
- In most neurons, the concentration of
  - K^+ is highest inside the cell
  - Na^+ is highest outside the cell
- **Sodium-potassium pumps** use the energy of ATP to maintain these K^+ and Na^+ gradients across the plasma membrane
  - Pumps 3 Na^+ out for every 2 K^+ in

- The opening of **ion channels** in the plasma membrane converts the chemical potential energy of the ion gradients to electrical potential energy
  - As ions diffuse through channels, they carry with them units of electrical charge
- Ion channels are selectively permeable, allowing only certain ions to pass through
- A resting neuron has many open potassium channels, allowing K^+ to flow out
- The resulting buildup of <u>negative</u> charge within the neuron is the major source of membrane potential

Figure 37.6


Key
Na+
K+
Sodium-potassium pump
Potassium channel
Sodium channel
OUTSIDE OF CELL
INSIDE OF CELL

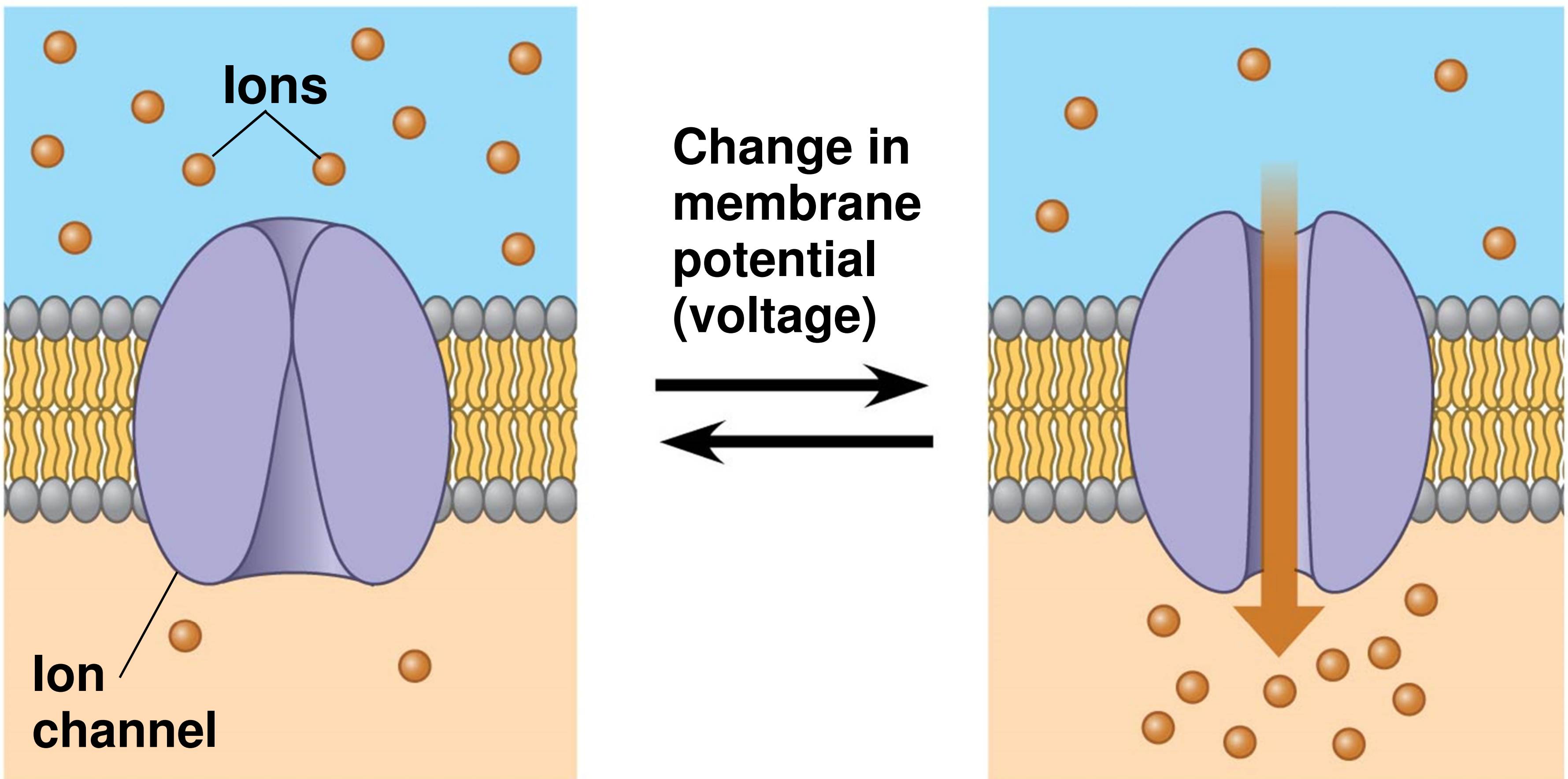


Animation: Resting Potential
Right click slide / Select play

Concept 37.3: Action potentials are the signals conducted by axons

- When a neuron responds to a stimulus, the membrane potential changes
- Changes in membrane potential occur because neurons contain **gated ion channels** that open or close in response to stimuli
  - Opening or closing of gated ion channels alters the membrane's permeability to particular ions
  - In turn alters membrane potential

Figure 37.9



(a) Gate closed: No ions flow across membrane.

(b) Gate open: Ions flow through channel.

Hyperpolarization and Depolarization

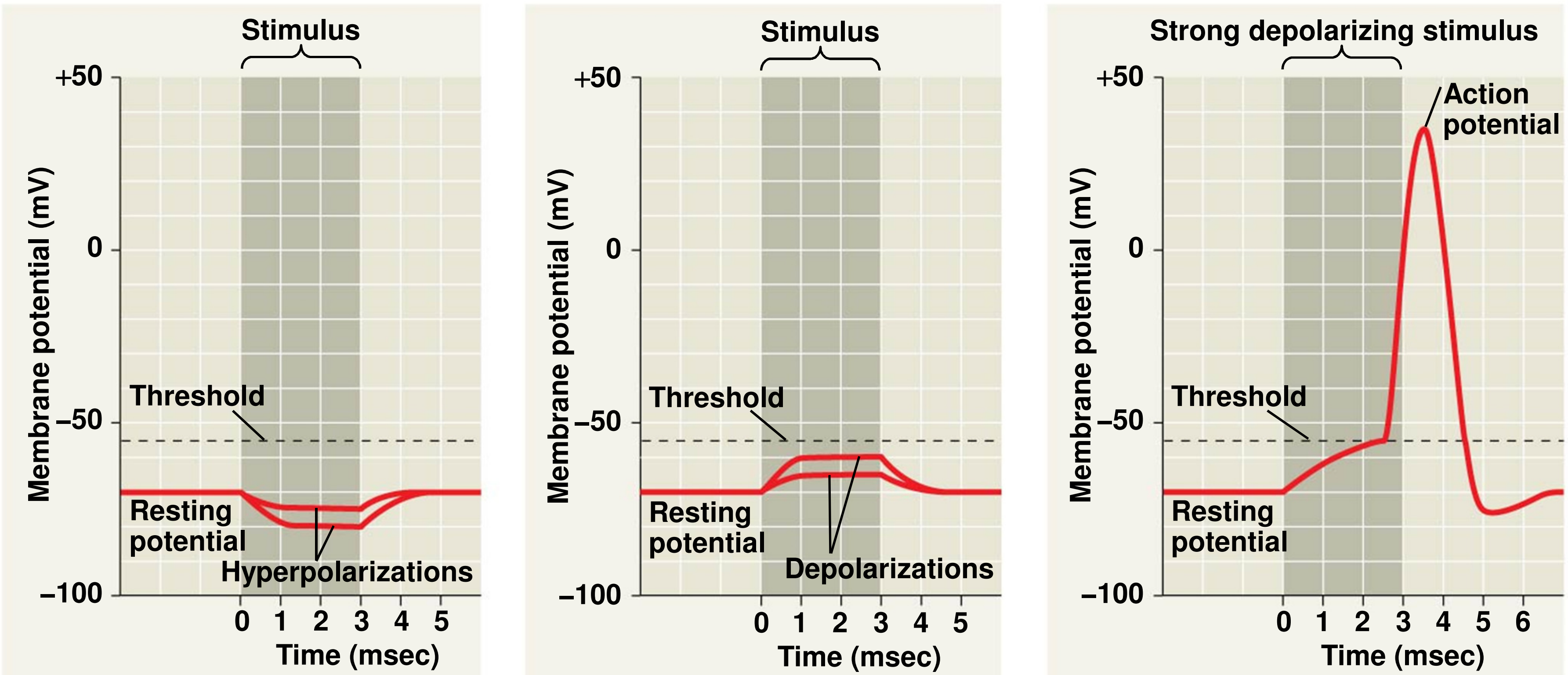
- When gated K^+ channels open, K^+ diffuses out, making the inside of the cell more negative
- This is **hyperpolarization**
  - An increase in magnitude of the membrane potential
  - Results from any stimulus that increases outflow of positive ions or inflow of negative ions
- Opening other types of ion channels triggers a **depolarization**
  - A reduction in the magnitude of the membrane potential
  - For example, depolarization occurs if gated Na^+ channels open and Na^+ diffuses into the cell

Graded Potentials and Action Potentials

- **Graded potentials** are changes in polarization where the magnitude of the change varies with the strength of the stimulus
  - A larger stimulus causes a greater change in membrane potential
  - Graded potentials decay with distance from the source

- If a depolarization shifts the membrane potential sufficiently, it results in a massive change in membrane voltage, called an **action potential**
  - Action potentials have a constant magnitude and transmit signals over long distances
- They arise because some ion channels are **voltage gated**, opening or closing when the membrane potential passes a certain level
  - Positive feedback triggers a very rapid opening of many voltage-gated ion channels
- Action potentials occur whenever a depolarization increases the membrane potential to a particular value, called the **threshold**
- Action potentials are all or none!

Figure 37.10



(a) Graded hyperpolarizations produced by two stimuli that increase membrane permeability to K^+

(b) Graded depolarizations produced by two stimuli that increase membrane permeability to Na^+

(c) Action potential triggered by a depolarization that reaches the threshold

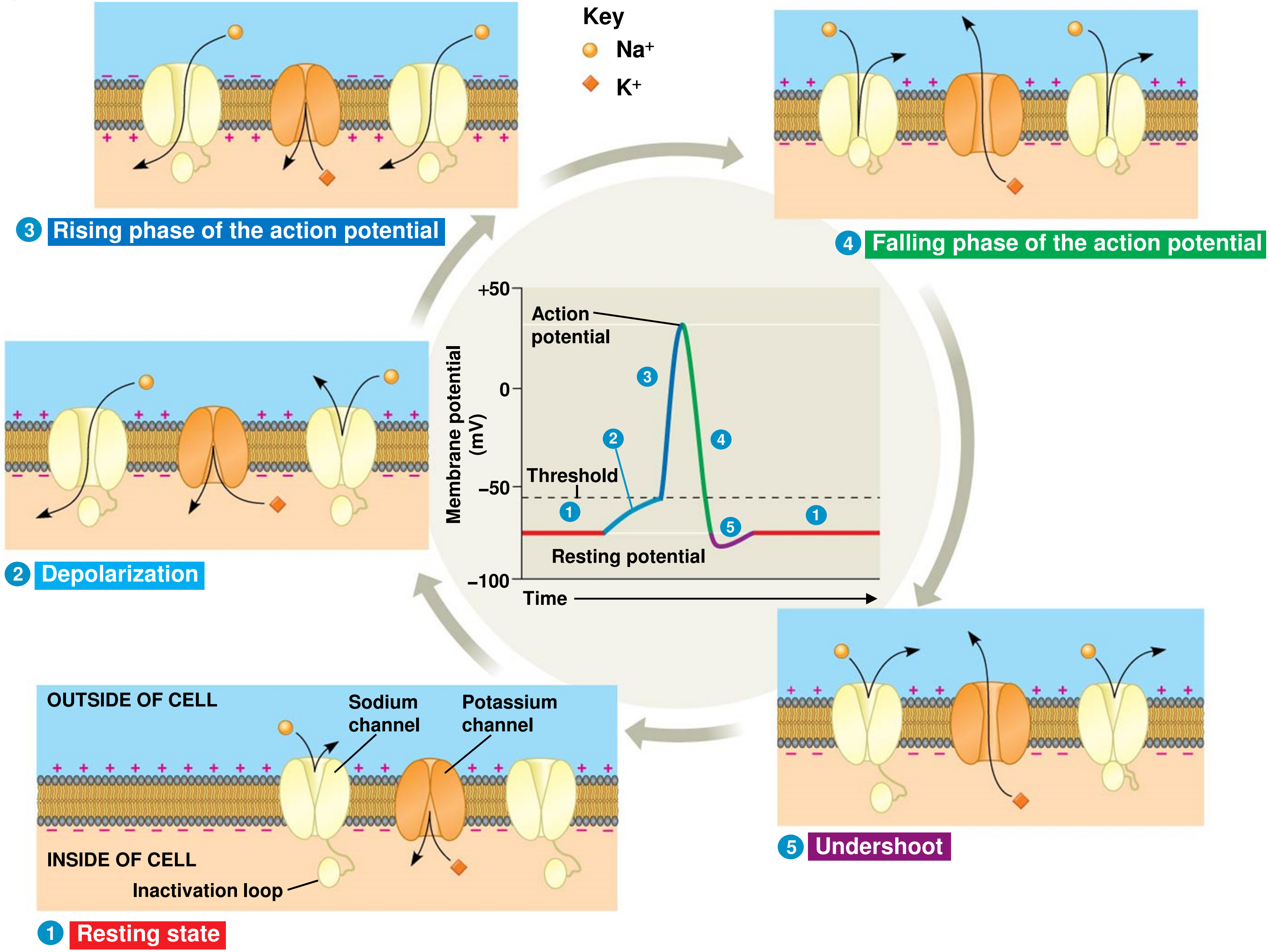
Generation of Action Potentials: *A Closer Look*

- Sodium channels open first, initiating the action potential
- Potassium channels open more slowly but remain open and function until the end of the action potential
- An action potential can be considered as a series of stages
- At resting potential
  1. Most voltage-gated sodium (Na^+) channels are closed; most of the voltage-gated potassium (K^+) channels are also closed

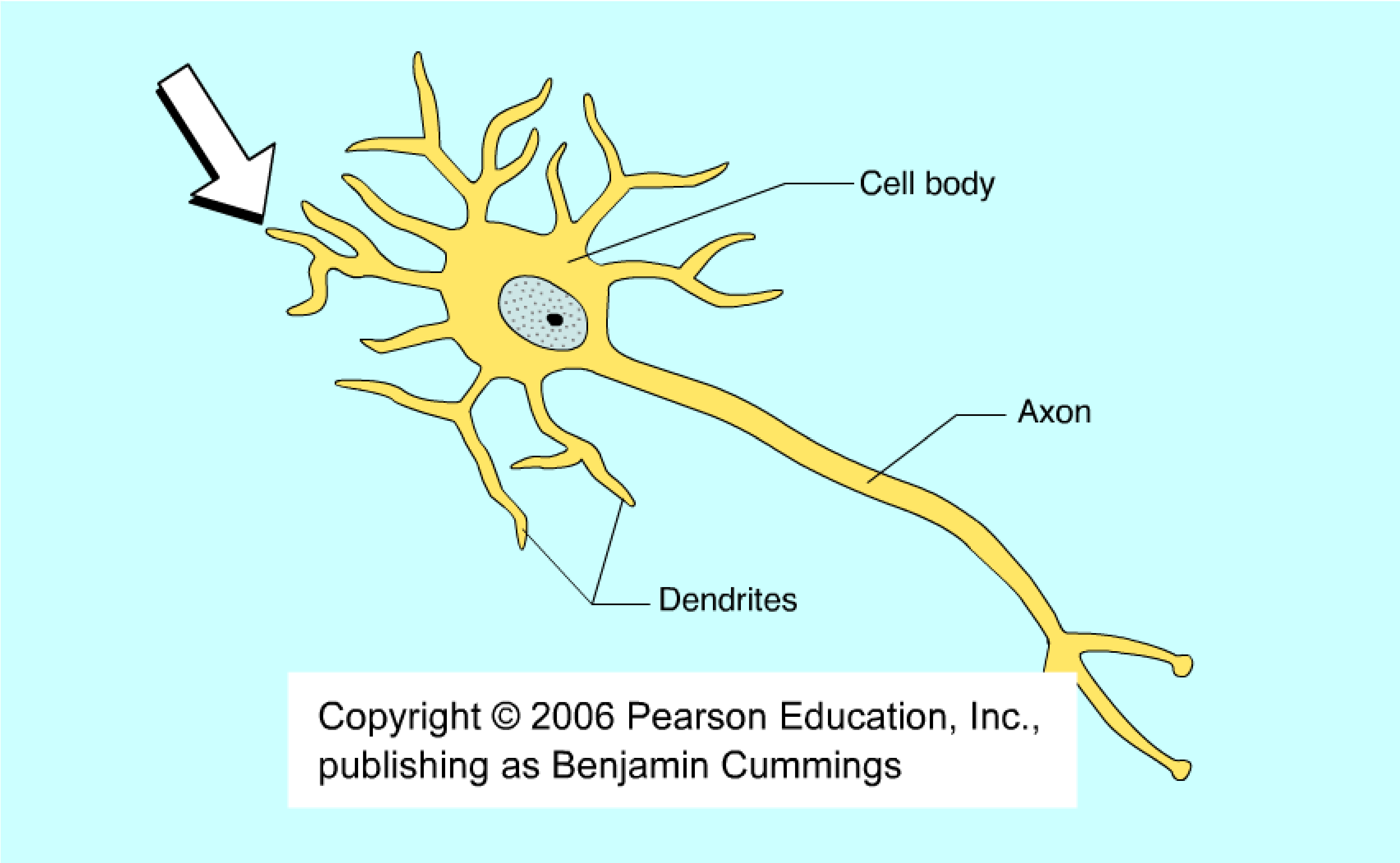
- When stimulus depolarizes the membrane

2. Some gated Na^+ channels open first and Na^+ flows into the cell
   - Causes further depolarization which opens more gated sodium channels
3. During the *rising phase*, the threshold is crossed, and the membrane potential increases
4. During the *falling phase*, voltage-gated Na^+ channels become inactivated; voltage-gated K^+ channels open, and K^+ flows out of the cell
5. During the *undershoot*, membrane permeability to K^+ is at first higher than at rest, and then voltage-gated K^+ channels close and resting potential is restored

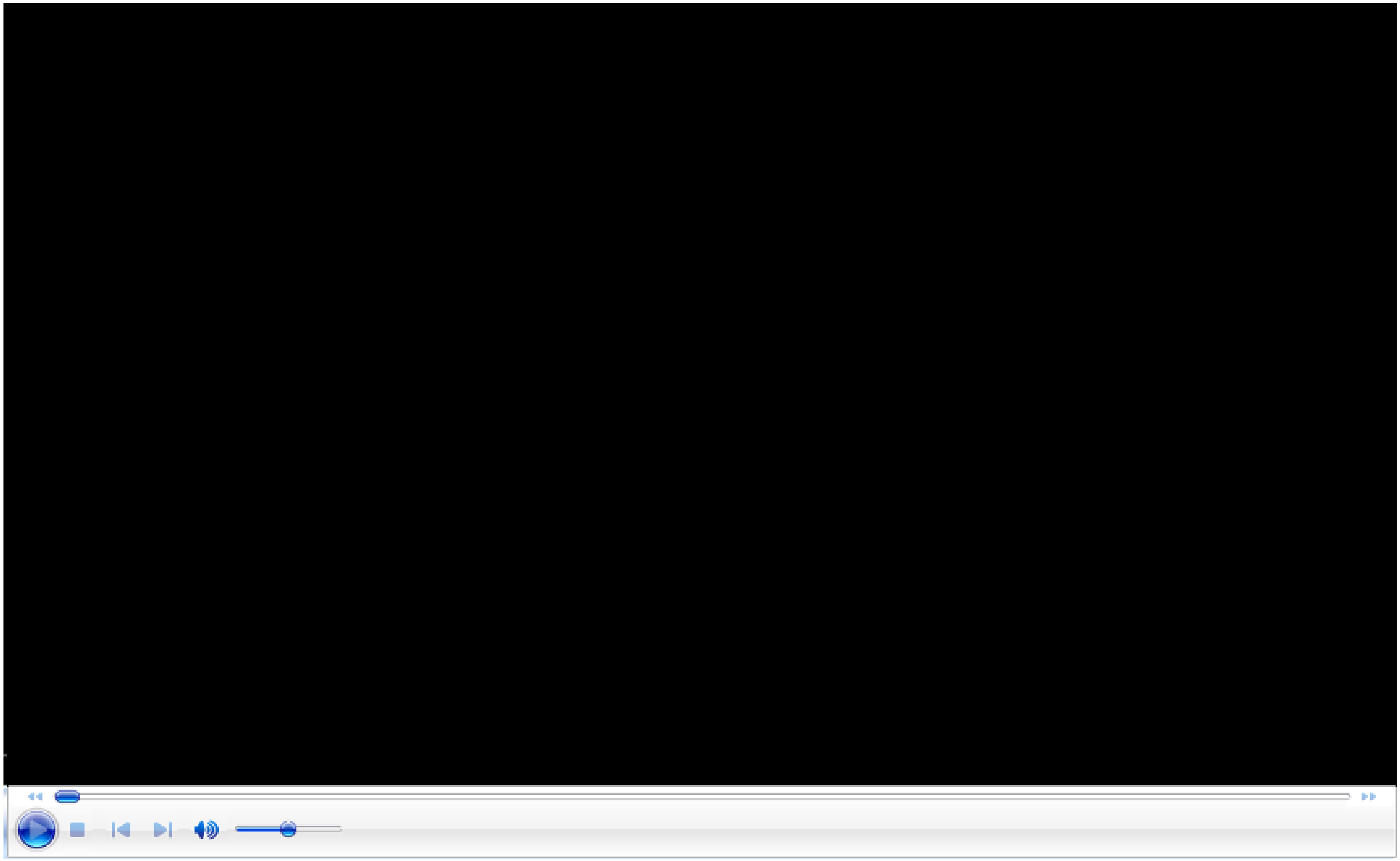
Figure 37.11



Key
Na+
K+
Rising phase of the action potential
Falling phase of the action potential
Depolarization
Undershoot
Resting state
OUTSIDE OF CELL
INSIDE OF CELL
Sodium channel
Potassium channel
Inactivation loop
Membrane potential (mV)
+50
0
–50
–100
Action potential
Threshold
Resting potential
Time
1
2
3
4
5



Animation: Action Potential
Right click slide / Select play



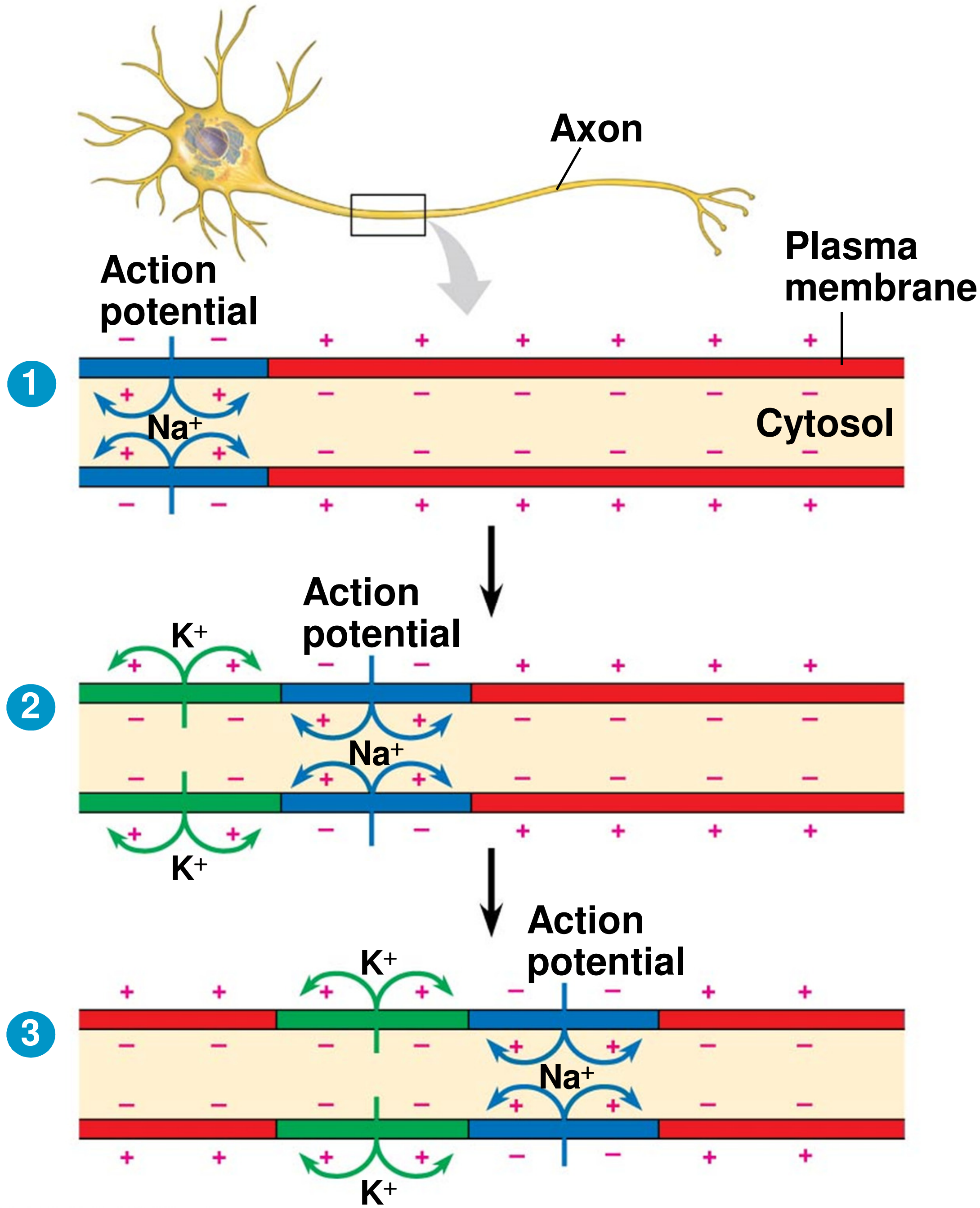
Video: How Neurons Work

- During the **refractory period** after an action potential, a second action potential cannot be initiated
- The refractory period is a result of a temporary inactivation of the Na^+ channels
  - Limits the maximum frequency at which action potentials can be regenerated
  - Ensures all signals in an axon travel in one direction
    - From cell body to axon terminals
- Differences in number of action potentials in a given time are the only variable in how information is encoded and transmitted along axon

Conduction of Action Potentials

- At the site where the action potential is initiated (usually the axon hillock), an electrical current depolarizes the neighboring region of the axon membrane
- Action potentials travel only toward the synaptic terminals
  - Inactivated Na^+ channels behind the zone of depolarization prevent the action potential from traveling backward

Figure 37.12-3



Evolutionary Adaptations of Axon Structure

- Wider axons
  - The speed of an action potential increases with the axon’s diameter
- Insulation
  - In vertebrates, axons are insulated by a **myelin sheath**, which enables fast conduction of action potentials
  - Myelin sheaths are produced by two types of glia:
    - **Oligodendrocytes** in the CNS
    - **Schwann cells** in the PNS

- Action potentials are formed only at **nodes of Ranvier**
  - Gaps in the myelin sheath where voltage-gated Na^+ channels are found
- Action potentials in myelinated axons jump between the nodes of Ranvier in a process called **saltatory conduction**
- A selective advantage of myelination is space efficiency

Figure 37.13

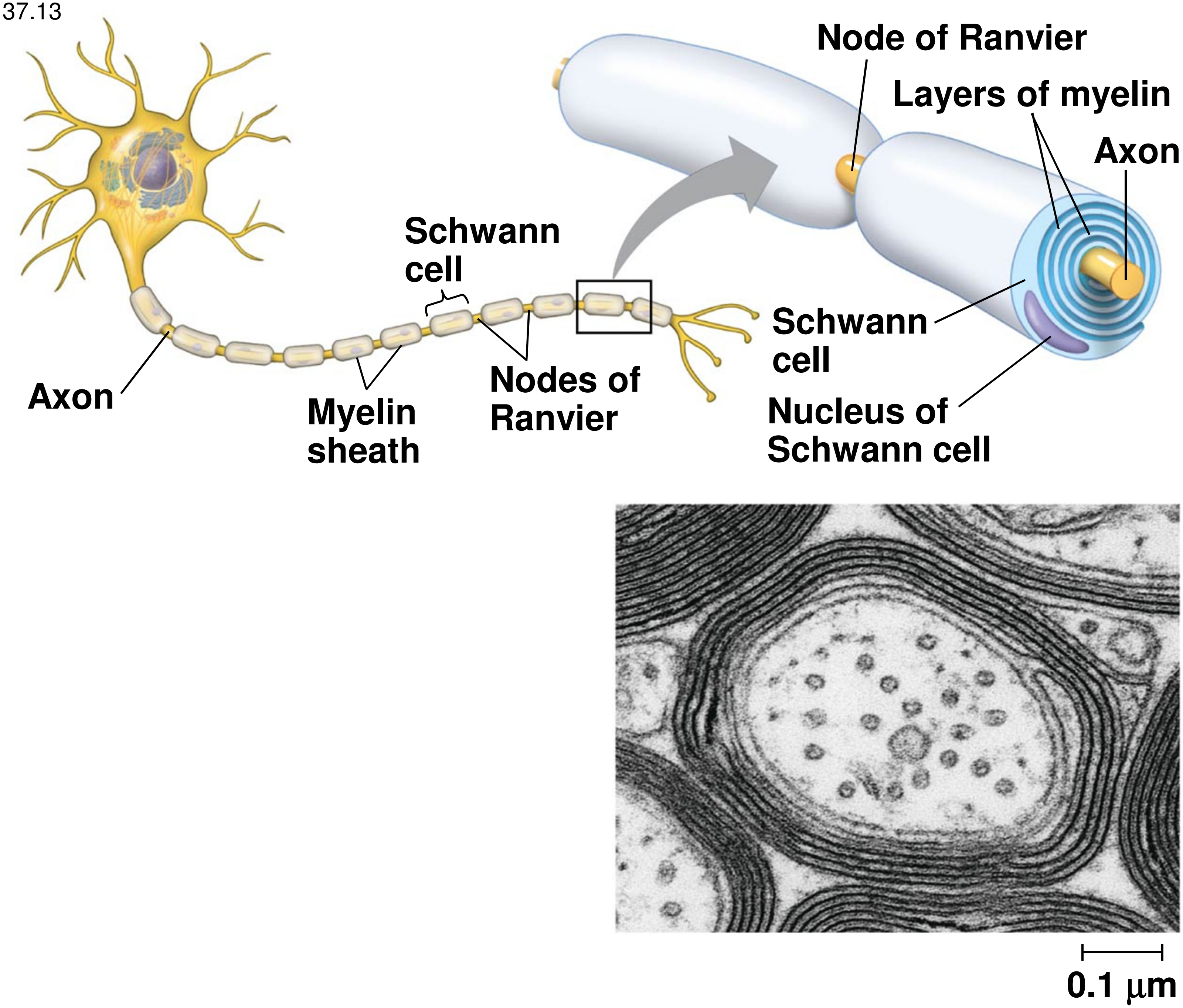
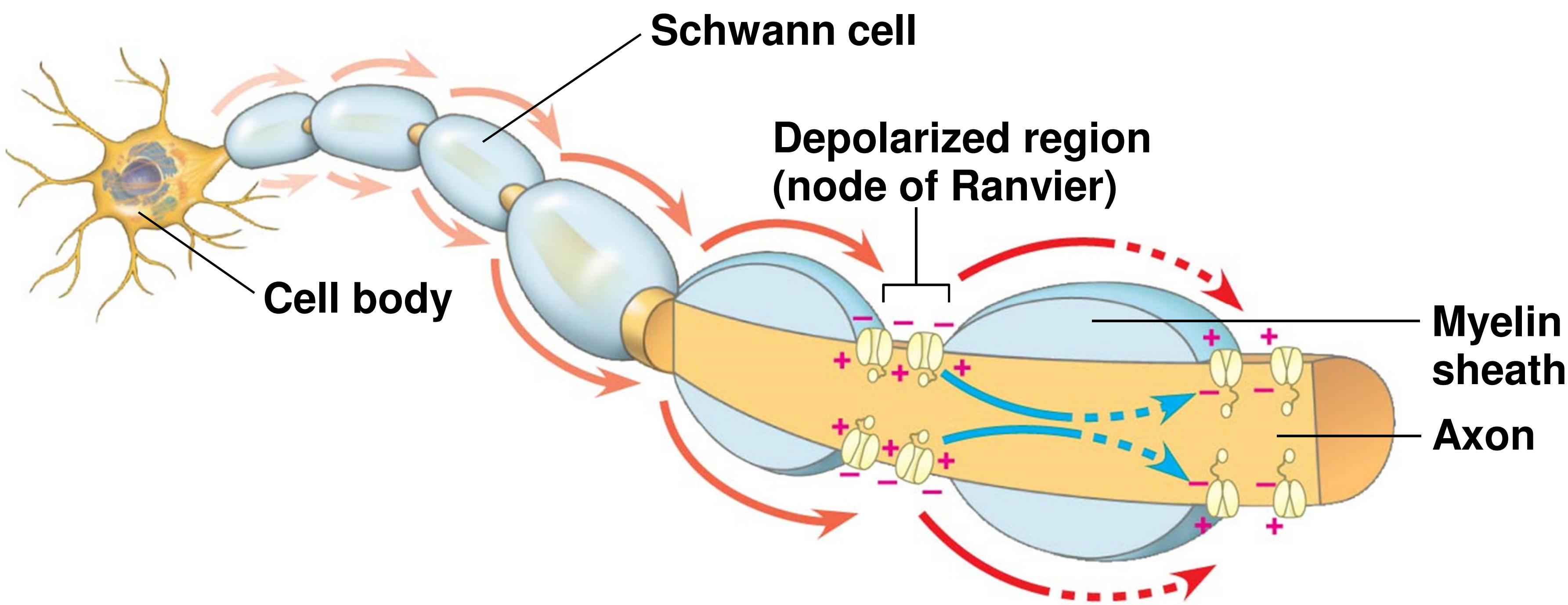

Node of Ranvier
Layers of myelin
Axon
Schwann cell
Axon
Myelin sheath
Nodes of Ranvier
Schwann cell
Nucleus of Schwann cell
0.1 μm

Figure 37.14

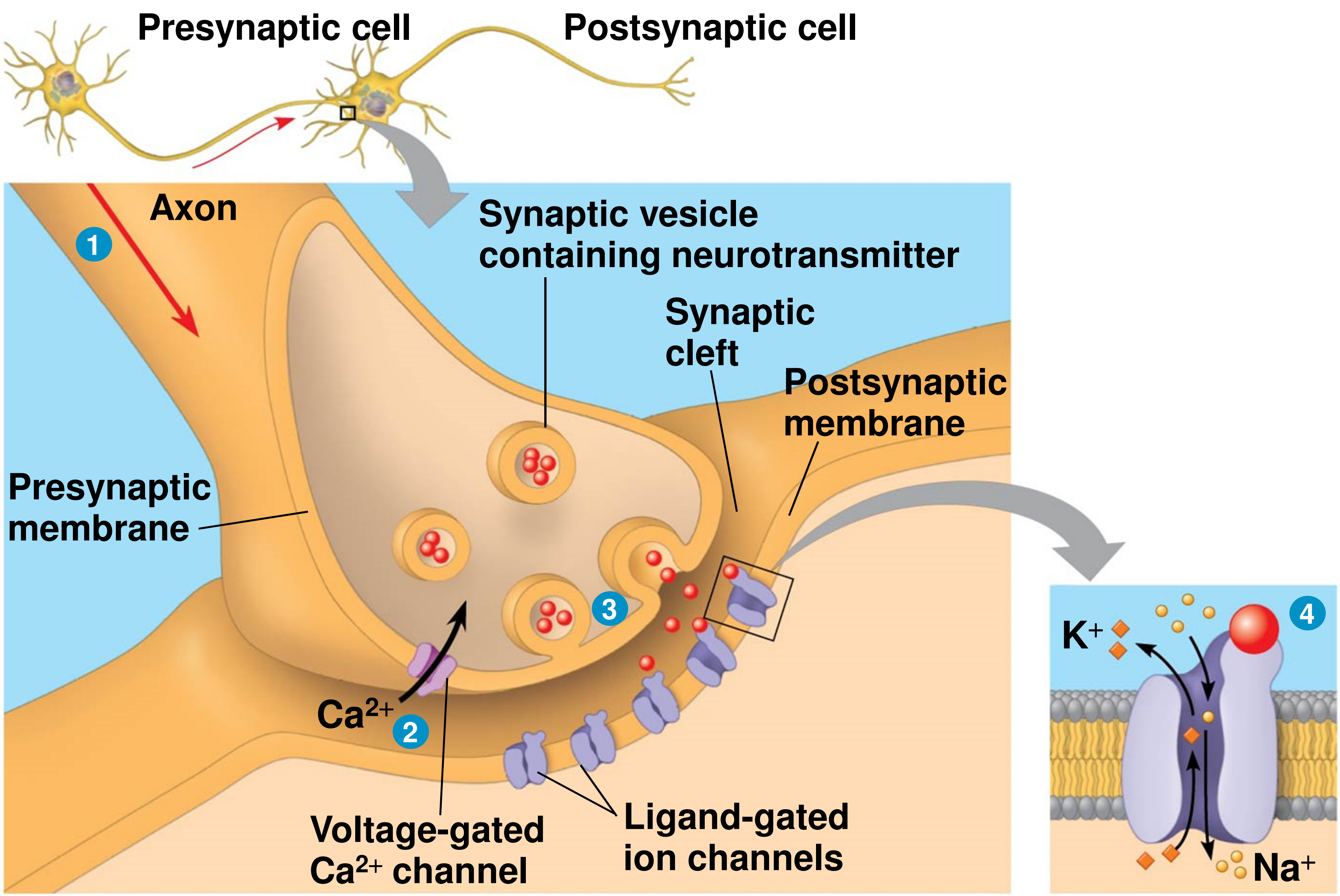

Schwann cell
Depolarized region
(node of Ranvier)
Cell body
Myelin
sheath
Axon

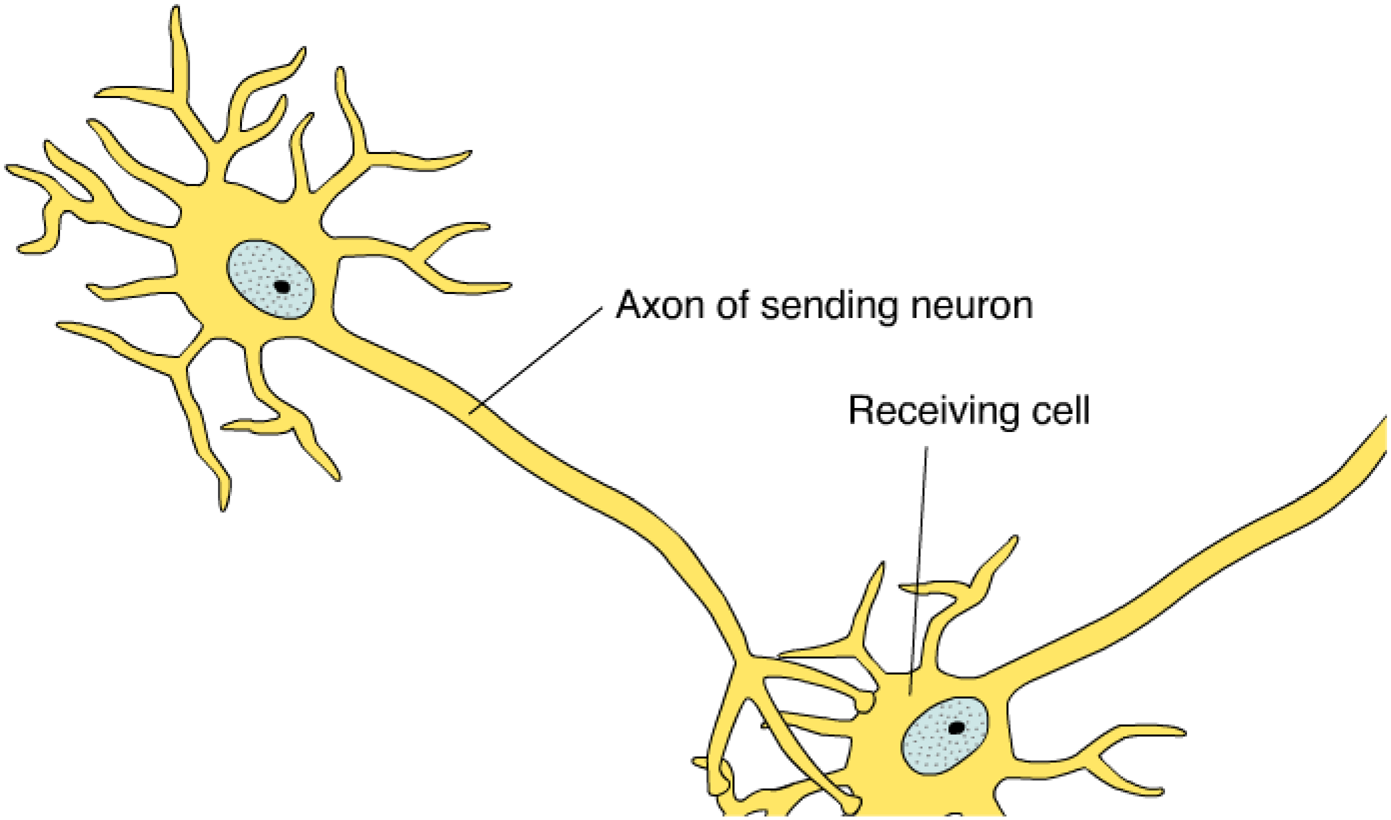
Concept 37.4: Neurons communicate with other cells at synapses

- At electrical synapses, the electrical current flows from one neuron to another at gap junctions
- But most synapses are chemical synapses
  - A chemical neurotransmitter carries information from the presynaptic neuron to the postsynaptic cell
  - Information is much more readily modified at chemical synapses than at electrical synapses

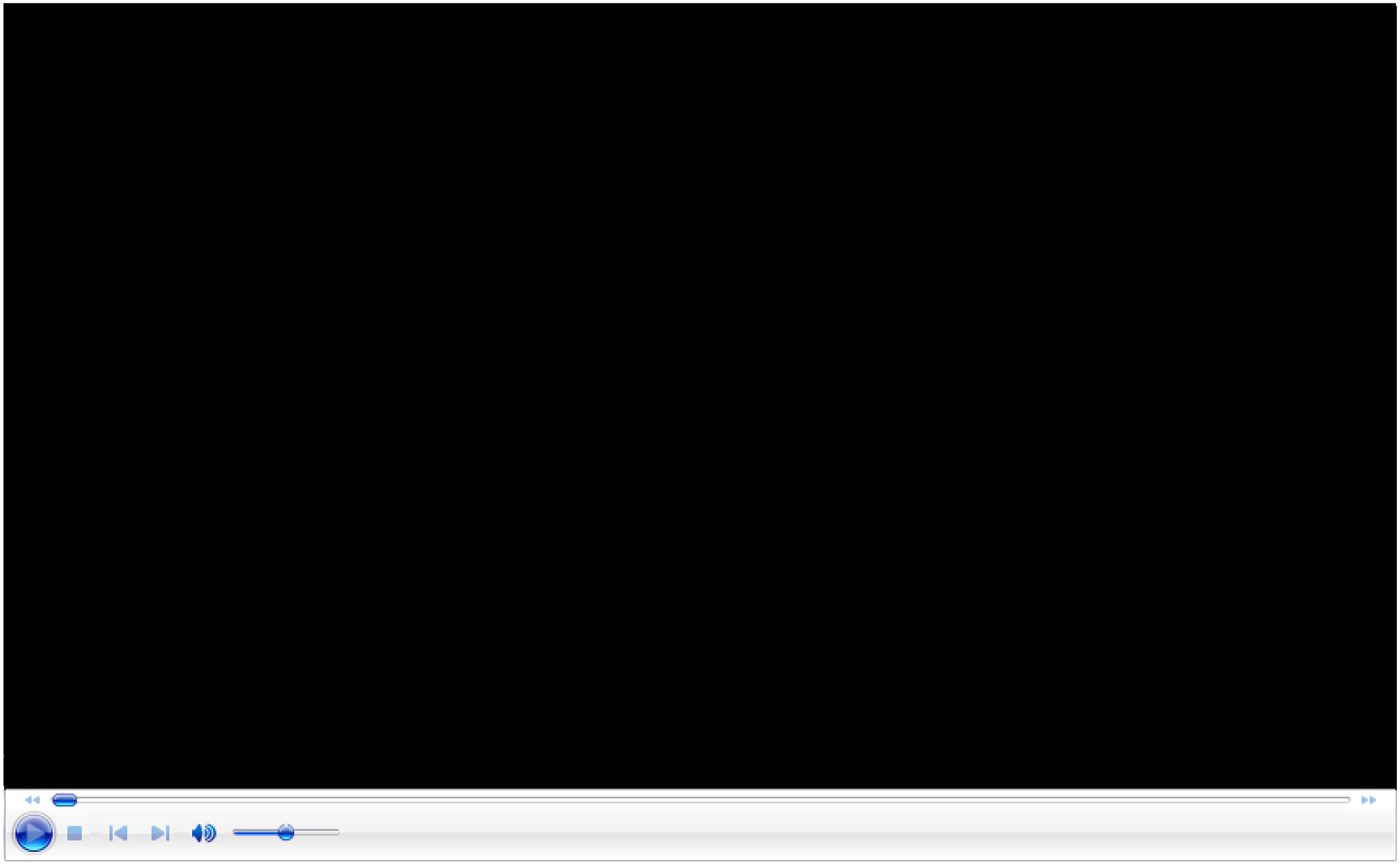
- The presynaptic neuron synthesizes and packages the neurotransmitter in *synaptic vesicles*
- The arrival of the action potential at a synaptic terminal causes the release of the neurotransmitter
- The neurotransmitter diffuses across the *synaptic cleft* and is received by the postsynaptic cell
- Neurotransmitter binds to and activates a specific receptor in the membrane
- This triggers a response in the postsynaptic cell

Figure 37.15


Presynaptic cell
Postsynaptic cell
Axon
1
Synaptic vesicle containing neurotransmitter
Synaptic cleft
Postsynaptic membrane
Presynaptic membrane
3
Ca2+
2
Voltage-gated Ca2+ channel
Ligand-gated ion channels
K+
4
Na+



Animation: Synapse
Right click slide / Select play



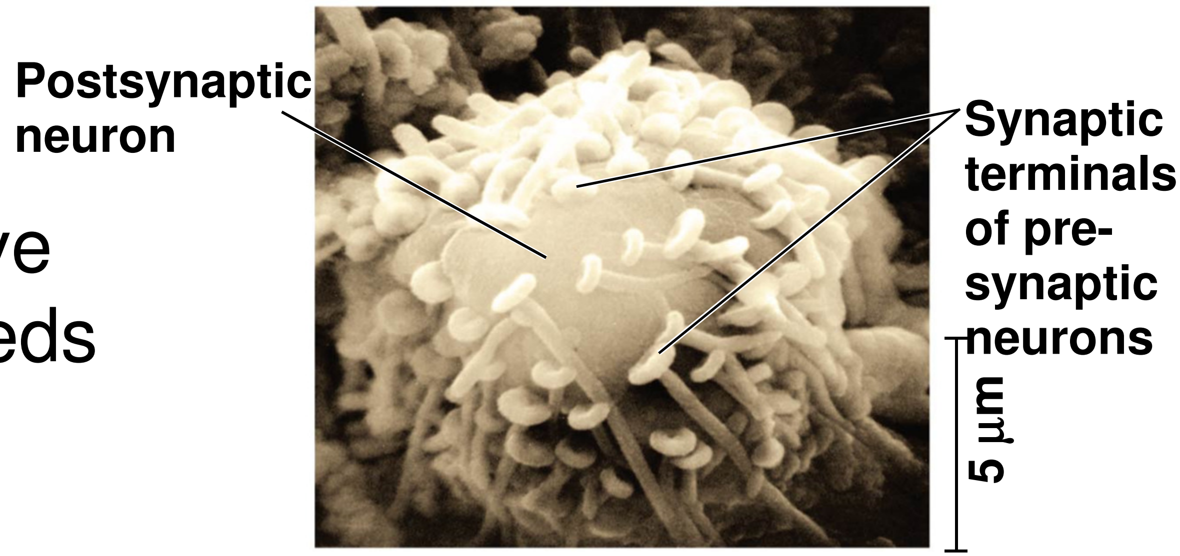
Video: How Synapses Work

Generation of Postsynaptic Potentials

- Direct synaptic transmission involves binding of neurotransmitters to **ligand-gated ion channels** in the postsynaptic cell
- Neurotransmitter binding causes ion channels to open, generating a postsynaptic potential
- Postsynaptic potentials fall into two categories
  - **Excitatory postsynaptic potentials (EPSPs)** are <u>de</u>polarizations that bring the membrane potential toward threshold
  - **Inhibitory postsynaptic potentials (IPSPs)** are <u>hyper</u>polarizations that move the membrane potential farther from threshold

Summation of Postsynaptic Potentials

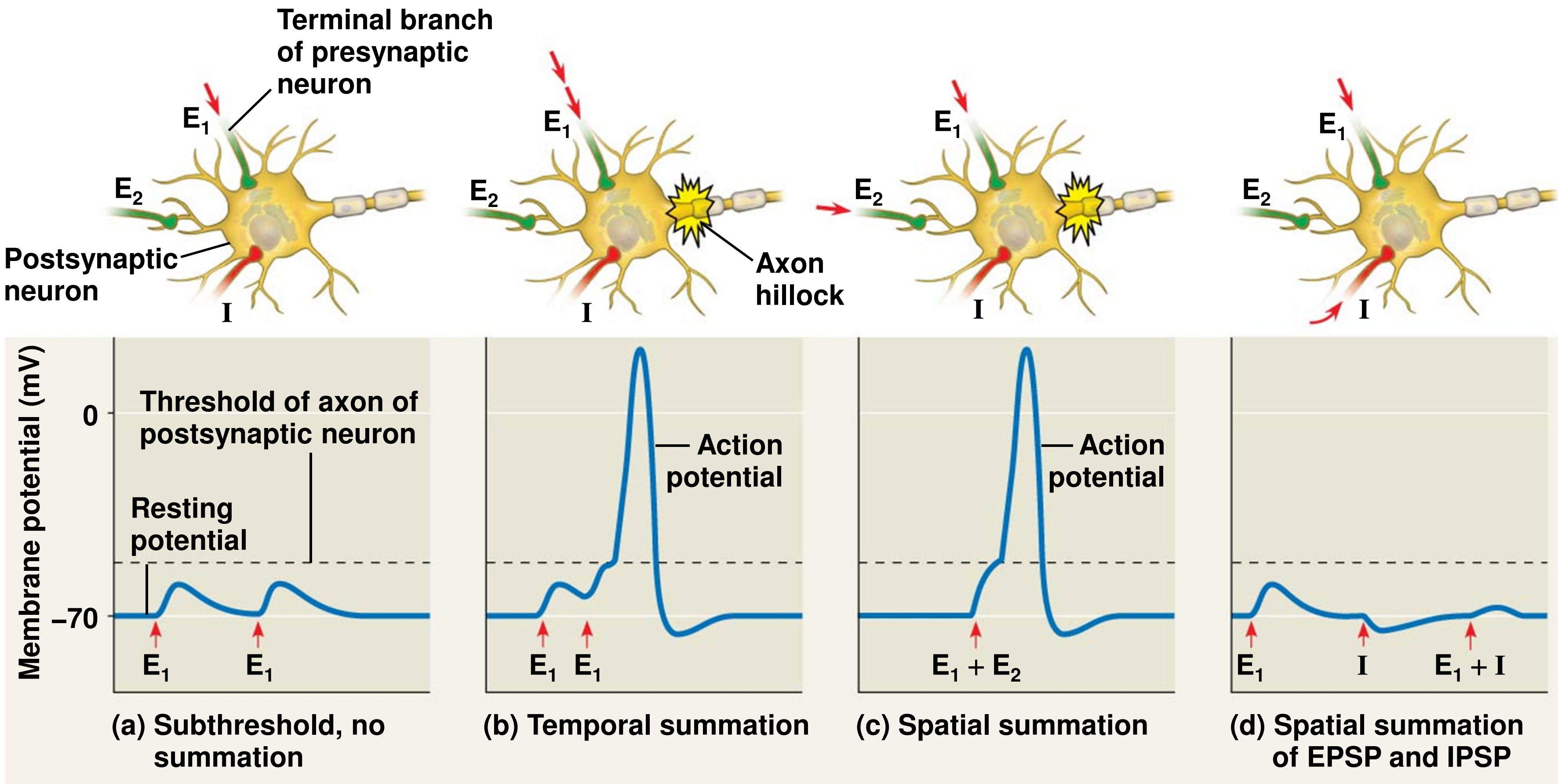
- The cell body of one postsynaptic neuron may receive inputs from hundreds or thousands of synaptic terminals



- As a graded potential, a postsynaptic potential becomes smaller with distance from the synapse
  - A single EPSP is usually too small to trigger an action potential in a postsynaptic neuron

- If two EPSPs are produced in rapid succession, an effect called **temporal summation** occurs
  - EPSPs add together
- In **spatial summation**, EPSPs produced nearly simultaneously by different synapses on the same postsynaptic neuron can also add together
- The combination of EPSPs through spatial and temporal summation can trigger an action potential
- Through summation, an IPSP can counter the effect of an EPSP
- The summed effect of EPSPs and IPSPs determines whether an axon hillock will reach threshold and generate an action potential

Figure 37.17


Terminal branch of presynaptic neuron
E1
E2
Postsynaptic neuron
I
Axon hillock
Membrane potential (mV)
0
–70
Threshold of axon of postsynaptic neuron
Resting potential
Action potential
E1 + E2
E1 + I
(a) Subthreshold, no summation
(b) Temporal summation
(c) Spatial summation
(d) Spatial summation of EPSP and IPSP

Neurotransmitters

- Signaling at a synapse brings about a response that depends on both the neurotransmitter from the presynaptic cell and the receptor on the postsynaptic cell
- A single neurotransmitter may have more than a dozen different receptors
- **Acetylcholine** is a common neurotransmitter in both invertebrates and vertebrates

Acetylcholine

- Acetylcholine is vital for functions involving muscle stimulation, memory formation, and learning
- A number of toxins disrupt neurotransmission by acetylcholine
  - Nerve gas sarin
    - Triggers paralysis and death
  - Bacterial toxin that causes botulism

- **Glutamate** (rather than acetylcholine) is used at the neuromuscular junction in invertebrates
- **Gamma-aminobutyric acid (GABA)** is the neurotransmitter at most inhibitory synapses in brain
- **Norepinephrine** and the chemically similar ephinephrine are excitatory neurotransmitters in the autonomic nervous system (involuntary)
- **Dopamine** and **serotonin** affect sleep, mood, attention, and learning
- **Endorphins** decrease our perception of pain
  - Opiates (drugs like morphine and heroin) bind to the same receptors as endorphins and produce the same physiological effects